NON-VACUUM PROCESSING OF CIGS SOLAR CELLS ON FLEXIBLE POLYMERIC SUBSTRATES

Vijay K. Kapur, Ashish Bansal, Phucan Le, Omar Asensio and Neil Shigeoka
International Solar Electric Technology Inc., (ISET),
8635 Aviation Blvd. Suite 'E', Inglewood, CA 90301, USA.

ABSTRACT

Using an ink based non-vacuum process CIGS solar cells were successfully fabricated on a flexible polymeric 'Upilex' substrate. A thin foil (0.001") of 'Upilex' was metallized by sputter deposition of 0.4 µm thick layer of Mo and CIGS solar cells were fabricated on it. 'Upilex' foil along with various device layers on it, withstood the fabrication conditions of ISET's process in which the maximum temperature was raised to 500^{o} C. A CIGS solar cell with AM0 efficiency of 8.0 % and specific power density >1280 watts/Kg was fabricated. With further process optimization we expect to achieve AM0 of 10% and power density >1500 watts/Kg in CIGS solar cells.

1. INTRODUCTION

For the last few years interest in flexible thin film solar cells has been growing for space power applications. The key focus in these applications has been to increase the specific power density of the solar cells beyond 1000 watts/Kg. Obviously thin film solar cells fabricated on flexible substrates offer the potential to meet this target compared with currently used crystalline silicon or gallium arsenide solar cells. Within the family of thin film solar cell materials i.e. Amorphous Silicon (a-Si), Cadmium Telluride (CdTe) and Copper Indium Gallium Selenide (CIGS), the most promising candidate material is CIGS. For space power applications, CIGS solar cells are considered favorably because of their tested resistance to radiation damage in outer space [1] and their overall stability. Additionally, among the thin film PV technologies, CIGS solar cells have achieved the highest conversion efficiency of 19.2% [2]. It is generally assumed that the efficiency of single junction CIGS solar cells will exceed 20% in the near future. Along with the choice of a proper light-weight and flexible substrate, the stability and high efficiency in the solar cells fabricated on the chosen substrate are the critical factors in achieving power densities greater than 1000 watts/Kg.

With the proliferation of wireless communication and portable electronic gadgets, interest in light-weight and flexible solar cells as portable battery chargers in terrestrial markets is also growing. The power density of commonly available crystalline silicon modules encapsulated with cover glass, is the range of 10-12 watts/Kg. For specialized and portable applications they are quite heavy and inconvenient. For terrestrial markets, in addition to the convenience factors (light-weight, flexibility), cost lowering of solar chargers is an even more important goal than increasing the power density. Keeping the low- cost goal in focus, ISET has developed and patented a non-vacuum, low cost process for fabricating CIGS solar cells. This process can be used both on rigid (glass) and flexible (metallic or polymeric foil) substrates [3].

In the past, ISET fabricated CIS/CIGS solar cells on Mo foil and polymeric 'Kapton' substrates. In these efforts absorber layers of CIS/CIGS were deposited using a 'Two Step Process' employing *vacuum deposition* of metallic precursors followed by their selenization [4,5] with promising results. However, recently, ISET successfully applied its *non-vacuum* process for fabricating CIGS solar cells on flexible metallic foil substrates [6].

Table 1 shows the weight contribution of a variety of flexible substrates of thickness 0.001" to the CIGS circuit. Using the non vacuum process, we have fabricated CIGS solar cells on Mo and Ti foils. At ISET we have not yet worked on stainless steel foils. To achieve the highest power density, CIGS solar cells should be fabricated on the lightest polymeric substrate such as 'Kapton' and 'Upilex'. These flexible substrates, with the exception of the Mo foil, are metallized by depositing a thin layer (0.4µm) of Mo by sputtering. The coefficients of expansion (CTE) of these substrates vary over a wide range. A CTE mismatch between the metallized substrate and the CIGS layer deposited on it can cause adhesion problems between the CIGS layer and the substrate. Therefore for every substrate the cell fabrication process has to be optimized to promote adhesion between the metallized substrate and CIGS layer deposited on it.

Table I. Power Density vs. Substrates

	CTE (X 10^6/°C)	Density g/cm^2	Weight£ g/m^2	Power Density* W/Kg
CIGS cell				
CIGS cell (with contacts & transparent cover layer)	7-9		33-40	
Flexible Substrates				
Molybdenum	4.8	10.2	259	455-466
Stainless Steel	12-17	7.9	205	555-574
Titanium	8.6	4.5	118	861-901
Kapton	20	1.42	40	1700-1863
Polyimide (Upilex-S)	12	1.47	41	1679-1838

* Assuming a 1 mil (25.4 µm) foil, 10% AM0 cell, and AM0 incident power = 1360 W/m^2. £ For Power Density calculations all substrates except Mo foil assume a 0.4µm thick Mo coating on one side of the substrate. Each 0.4µm Mo coating adds 4.1 g/m^2 to substrate weight. CTE = Coefficient of Thermal Expansion.

In this paper we describe some of the early results of using our non-vacuum process for fabricating CIGS solar cells on 'Upilex', a polyimide foil obtained from Ube Industries of Japan.

2. NON-VACUUM PROCESS

ISET's non-vacuum process has been described in detail previously [7, 8]. The attractive features of this process are; (i) uniform deposition of precursor coatings, (ii) high materials utilization, and (iii) low cost of capital equipment used. The most expensive item in the process equipment is the sputtering system that we have to use for metallizing glass or 'Upilex' substrate. As a combined effect of these attributes, the cost of manufacturing CIGS solar cells is projected to be well under $1.0/watt [9].

Impressive results have been obtained in CIGS solar cells fabricated on glass and Mo foil substrates using ISET's non-vacuum ink based process. Figures 1 and 2 show I-V characteristics of CIGS solar cells fabricated on glass and Mo foil respectively.

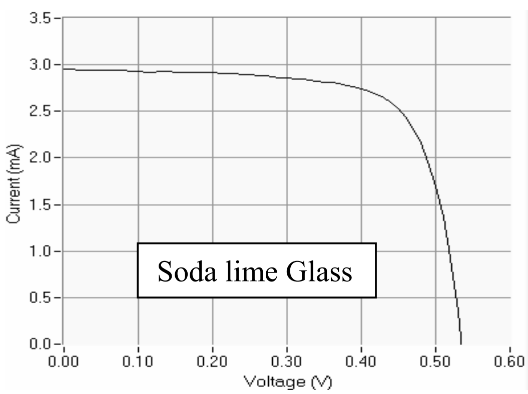

Fig. 1 I-V Curve of a CIGS solar cell on soda lime glass with 13.6% AM1.5 efficiency. Voc = 0.54 V, Jsc = 35.2 mA/cm^2, FF = 0.72.

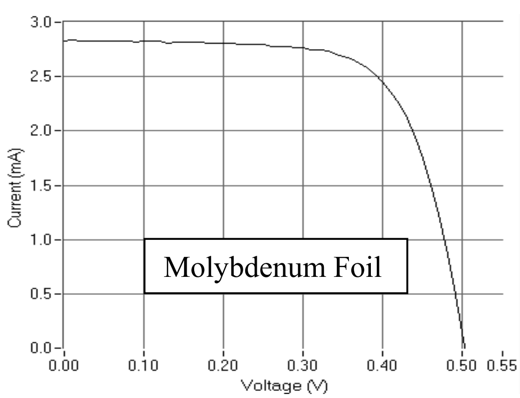

Fig. 2 I-V Curve of a CIGS solar cell on molybdenum foil with 11.7% AM1.5 efficiency. Voc = 0.50 V, Jsc = 33.7 mA/cm^2, FF = 0.69.

Presently, we are using this non-vacuum process to fabricate CIGS solar cells on polyimide substrates. This effort requires a significant amount of process optimization for handling thin foils of 'Upilex', stress minimization and adhesion promotion. In addition to its light weight, the advantage of using non-conducting polyimide substrate is the possibility of monolithically integrating solar cells. Moreover using flexible substrates, solar cells can be manufactured in a continuous mode of roll-to-roll processing.

3. WORKING WITH 'UPILEX' SUBSTRATES

In ISET's non-vacuum process the precursor coating of mixed oxides with a pre-determined Cu/(In+Ga) ratio is converted into a CIGS absorber layer by first reducing the precursor layer to alloys of Cu-In-Ga followed by their selenization. Reduction is carried our under a mixed-gas atmosphere of H_2 and N_2 gases and the selenization is carried out under a mixed-gas atmosphere of H_2Se and N_2 gases. During these steps a substrate is cycled through temperatures in the range of 500-550^{o}C. Therefore it is critical that the polymeric substrate used can withstand the processing conditions of temperature and the gaseous environment. Though the published data on 'Upilex' by its manufacturer suggests that it can withstand temperature up to 550^{o}C when heated in air or N_2, we tested its performance up to 550^{o}C under gaseous atmospheres that we use for reduction and selenization steps in our process. Figure 3 shows thermogravimetric (TGA) data for a piece of an 'Upilex' foil that was heated to 550^{o}C at a rate of 10^{o}C. It took about 55 minutes to achieve 550^{o}C and thereafter the sample was held at this temperature for another period of 30 minutes. The TGA data showed no loss of weight suggesting that under these conditions 'Upilex was stable. However, we noticed when the 'Upilex' was exposed to temperatures >500^{o}C it tends to have some discoloration and also becomes brittle. Based on this information, we decided to adjust our process parameters keeping the maximum temperature experienced by the 'Upilex' foil to be 500^{o}C or less.

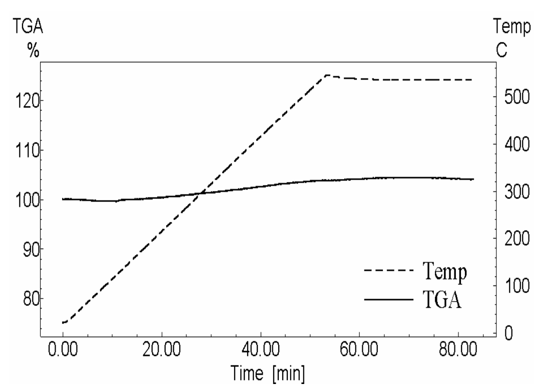

Fig. 3 Thermogravimetric analysis of a Upilex sample indicates that the substrate can withstand typical process temperatures (450-550°C) without any degradation

Metallizing 'Upilex' by sputter deposition of Mo on it also poses some challenges. Initially the sputtered coatings on 'Upilex' were highly stressed and coating Upilex with Mo on one side caused the substrate to curl up and made it difficult to handle. Deposition of Mo on both sides of Upilex minimized curling of the substrate. After optimization of the sputtering conditions, we were able to obtain highly adherent and smooth Upilex/Moly substrates.

Using the ink based non-vacuum process we have fabricated a number of CIGS solar cells on Upilex. So far the best cell made with non-vacuum process has an AM1.5 efficiency of 8.9% which is equivalent to at least 8.0% for an AM0 spectrum (Fig. 4).

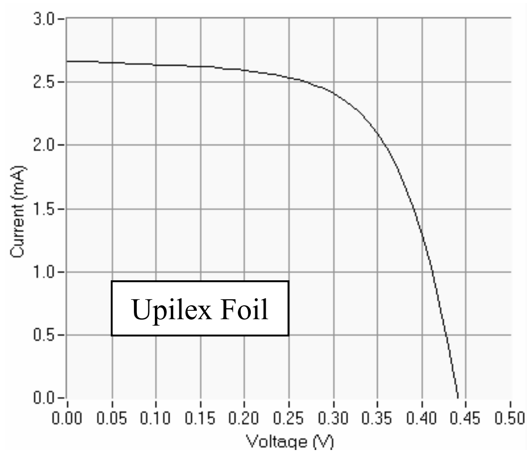

Fig. 4 I-V Curve of a CIGS solar cell on 1 mil Upilex foil with 8.9% AM1.5 efficiency (AM0 = 8.0%). Voc = 0.44 V, Jsc = 31.8 mA/cm^2, FF = 0.63.

Examining the cell parameters it is clear that V_{oc} of the cell is low even though we have Ga in the absorber layer. The Ga present in the absorber tends to distribute unevenly towards the back Mo contact in CIGS absorbers that are prepared via the selenization process. This preferential accumulation of Ga near the back Mo contact leaves the absorber layer near the junction with little or no Ga in it. Thus the CIGS layer behaves as it has no Ga in it resulting in low V_{oc} values in solar cells. We are currently working to improve the Ga distribution in the absorber layer and hope to fabricate CIGS solar cells using the ink process with much higher efficiencies. As a result of some of our efforts we have already improved the V_{oc} values in solar cells fabricated on glass substrates as shown in Figure 1. Additionally there is plenty of room for further improvements in the current density and in the fill factor which are likely to result in solar cells with much higher efficiencies.

Figure 5 has the AM0 power densities of all of the CIS/CGS solar cells that ISET has fabricated on flexible substrates. CIS Solar cells fabricated on 'Kapton' were processed using the vacuum deposition of the precursor layers. All other cells were fabricated using the non-vacuum processing. With the best cell fabricated on 'Upilex' we have already achieved a AM0 power density exceeding 1280 Watts/Kg. With modest and achievable improvements in these solar cells resulting in AM0 efficiency of 10% the power density will easily exceed 1500 Watts/Kg. We are quite confident of hitting this goal. In our continued efforts we plan to fabricate monolithically integrated sub-modules on 'Upilex' using the non-vacuum process.

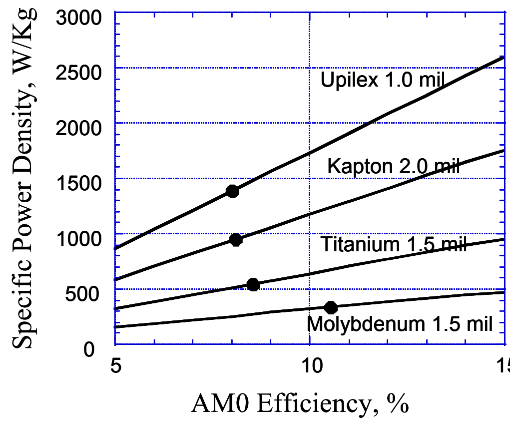

Fig. 5 Specific power density as a function of the efficiency of the CIGS solar cell. The lines show the calculated specific power density. The dots represent cells made on the respective substrates at ISET.

4. CONCLUSIONS

The work presented in this paper has demonstrated the feasibility of using ISET's non-vacuum process for fabricating thin film CIGS solar cells on 'Upilex'. These CIGS solar cells with high power density, fabricated on light-weight and flexible substrates could be used for space power applications. The non-vacuum process was originally developed with a special focus on lowering the manufacturing cost of CIGS solar cells for terrestrial applications. Success in this project will result in a technology that could be used effectively for both space and terrestrial applications.

5. ACKNOWLEDGEMENTS

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